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Packaging Design Alternatives for Meat Products

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Abstract

This chapter connects the main requirements of meat product preservation with the most used plastic packaging structures, highlighting the role of packaging on the extension of food products shelf life and allowing their distribution and consumption in the most diverse areas of the world. An overview on the main degradation mechanisms of meat products is provided as background for the deeper discussions on flexible packaging films' compositions that is most used for meat packaging. Details on the performance of different sealing materials, gas barrier layers, and structural compositions as well as specific characteristics of packaging such as vacuum bags, shrink barrier bags, thermoforming, vacuum skin, and modified atmosphere packaging are discussed in this chapter serving as building blocks for an optimum packaging design, from food preservation to the final packaging end use. Finally, as part of an evolving world, new packaging trends are discussed, covering consumerism, sustainability, and functionality aspects.

Keywords: packaging, meat products, vacuum bags, shrink bags, skin packaging, modified atmosphere packaging, sealants, barrier resins, polyethylene, ionomers, polyamide, EVOH, PVDC

1. Introduction

The consumption of meat products refers back to the beginning of human history, with first ancient butcher activities believed to start around 10,000 BC [1]. Butchers are present in Bible parables and were an active community in ancient cities as Rome and London fostering the growth of pastoral economy around these places and supplying meat pieces to populations that could afford it. This arrangement was dominant till the eleventh century. The conservation and transportation of meat products were still scarce with rudimentary methodologies as salt and drying, limiting the industry to shops located into larger social agglomerates. Later on, during the 1700s the first slaughterhouse started to pack meat in the USA, fostering industry growth around cattle and pork, but still conservation and transportation were limited and challenging.

First ice trade companies were established in West Virginia, USA, during the early 1800s [2], and, with the volume expansion of ice commercialized during the late 1800s, the product was also a source of refrigeration for meat products across the USA and few other countries. With the advancements of refrigeration cooling systems, new containers and storehouses were designed to preserve perishable products and expand their movement among the countries, establishing logistic chains to transport chilled and frozen meat products safe and efficiently.

Another interesting finding during this era was the impact of CO₂ on meat preservation; it was found during meat product shipment from Australia to England that the use of solid CO₂ extended the shelf life more than meat held under ice [3]. At this time, rudimentary packaging materials were used to reduce contamination possibilities from production center to consumers.

During the 1950s, however, an important revolution started, with the decline of bulk sales based on the intermediation of butchers on sorting, selecting, and serving the consumers and the raising of sales model based on supermarkets, with products competing to each other for consumers' attention. In this new dynamic, packaging gained another important function besides protect the food: the ultimate communication with potential consumers [4].

Packaging is today a critical vehicle to provide physical protection for the meat products from environmental treats and control microbiologic growth during the shelf life period. On the other hand, packaging is a single variable in a complex equation of meat quality that comprises the characteristics of animals (age, nutrition, raising conditions), sanitary conditions of slaughtering facilities, storage, and transportation conditions.

With increasing demand for fresh, highly nutritional, and tasty food, the meat product production chain has invested on animal health technology programs as well as controlled transportation methods to extend product shelf life and enhance product quality at consumption moment. A proper packaging design can certainly contribute to microbial control and, when associated to proper storage conditions, can preserve good-quality fresh meat products up to 10 times versus unpackaged products, a key element to reduce food waste.

The global beef market today is formed by global players, focused on local market demands as well as food exportations. Looking at global beef production, half of world production is divided within the USA, Brazil, the European Union, and China, being the European Union and Brazil the two largest red meat exports in the world. Brazil has the largest commercial cattle herd in the world, adding 208 million heads, being almost 30 million slaughtered in 2016 [5].

2. Main deterioration mechanisms of meat products

The quality of meat production started with careful animal raising since pre-natal and feeding during its life, forming a proper carcass, fat depositions, as well as number and size of muscular fibers. The overall concept of a high quality of meat products is based on a combination of several factors that can be correlated or individually analyzed. The main parameters used by industry can be described as (1) visual quality (color, muscle, and fat), (2) gustatory quality (texture, flavor, and odor), (3) nutritional quality, and (4) food safety [6]. The final product quality starts with proper handling of animals, primarily the food provided to them and living conditions, followed by adequate processing installations and controls, packaging, transportation, and storage. Several regulations and norms are applied in the different countries as best procedures to increase overall food quality and safety for consumers.

During storage meat products deteriorate because of pigment oxidation, oxidative rancidity, microbial growth, and even surface dehydration. Color is one of the key attributes evaluated by consumers during purchasing process, and it is determined by the state of the meat pigment, myoglobin, present into the meat surface. Fresh meat color changes to red, also known as "blooming," and is a derivative from the presence of oxymyoglobin (oxygenated state of myoglobin). In the absence of oxygen, the meat color turns into purple tone, with predominance of

reduced myoglobin (deoxymyoglobin) on meat surface. Fresh meat products can also become brownish red with oxidation of myoglobin, generating metmyoglobin. This reaction occurs when small amounts of residual oxygen inside the vacuum-packaged fresh meat react with the pigment right after the vacuum packaging. The attractive red-pink color of cooked, cured meats is essentially an association of nitric oxide with native meat pigment that results in nitrosylhemochrome. This pigment is very sensitive to oxygen and light, so cured meats can fade during storage or under retail display if not protected by a proper package. Other inherent variables of beef products can affect color, such as age, gender, feed and pH, and microbial contamination. Storage conditions can also change the color of beef; especially when UV light is used at retailers, it can accelerate the conversion to metmyoglobin and change the color to brown tones. High-storage temperature also promotes discoloration.

Other quality parameters such as gustatory quality and food safety are strongly dependent on bacterial activities. The presence of microorganisms can lead to enzymatic deterioration and oxidation, but microbacterial growth is determined in several studies as the most important contributing factor for meat products' decay [6–8]. Vacuum-packaged meat products, in general, present extended shelf life compared to products in contact with air. There are two main bacteria that can proliferate into packaged meat products: *Pseudomonas*, which are dominant when enough oxygen is allowed into the package but suppressed by vacuum, and lactobacillus that can grow in vacuum environments. Both types are dominant and can outgrow each other under their favored conditions. The basic principle of meat packaging material design is to depress *Pseudomonas* growth and allow lactobacillus to proliferate, a genus of bacteria with a lower potential for deterioration. Proper permeability and gas composition around the product allowed by packaging materials combined with refrigerated conditions provide longer shelf life desired for beef products, reaching up to 120 days. Microbial spoilage may lead to changes in color and appearance as well as off-odor generation due to volatile metabolites.

The presence of oxygen can also lead to oxidation reactions of fats, accelerating odor changes and discoloration. Low O₂ level also contributes to avoid lipid, reducing the decay rate of meat quality and contributing to extended shelf life. The uses of packages with modified internal atmospheres (modified atmosphere packaging (MAP)) using intermediate to high levels of carbon dioxide (CO₂) combined with lower or high levels of oxygen (O₂) are alternatives to control bacterial growth and also preserve red tone of packaged meat. The most popular MAP gas mixtures are composed of blends of CO₂ and O₂, with O₂ being responsible to maintain red blooming tone of meat and CO₂ impacting the bacterial growth, limiting microbial deterioration. N₂ can also be added to the mix as an inert gas to balance internal and external partial pressures and reduction permeation rates of CO₂ and O₂. Mixtures of 80% of O₂ and 20% of CO₂ associated to storage temperatures in the range of 4°C can preserve meat up to 12 days and maintain its red color [7].

An alternative methodology to manipulate meat color by gas mixtures is to add carbon monoxide (CO) into MAP mixture of CO₂ and N₂, preserving meat red for more than 20 days. This application is controversial as it can mask spoiled products from consumers but mainly due to severe safety concerns with gas leak aging during packaging process and the inhalation of CO after opening the package. In the USA it is allowed to add CO at 0.4%, but this same approach is banned in other parts of the world [7, 9].

Due to the high water content on fresh meat cuts, unpacked products can present quick visual deterioration and weight losses. The liquid is also present into packaged meat cut, having deep impact on product appearance. Chilled temperatures can reduce the amount of exudate, but shrink bags and absorbent liquid pads can improve shelf appeal. The presence of liquids exudate can also be a factor that

accelerates bacterial growth if environmental conditions allow, since it is rich in nutrients. This liquid fraction known as purge or drip is considered acceptable when found up to 2% of packaged product weight [6]; levels close to 4% are considered unacceptable and lead to economic losses.

In association with proper packaging processes, various preservation processes have been used for meat products over the years. Starting with drying and salting/curing, passing through chilled and frozen or heat treatment (from cooking till sterilization processes such as retort), food preservation methods generally rely on suppression of key elements for deterioration (water, oxygen, light) and temperatures (cold and hot).

Additionally, food additives can be used to extend shelf life, as salts, sugar, liquid smoke, and spices and processes as smoking, etc. The uses of low temperature (-2 to -4°C) and freezing (below -15°C) are key methods for meat preservation used in the market due to the obtained reduction on the rate of microbiological growth. When water is frozen, all enzymatic processes and bacterial growth are reduced to a minimum, preserving meat quality for proper consumption in several cases beyond 12 months. The oxidative reactions, however, continue to affect meat quality with time through deteriorative mechanisms such as fat and pigment oxidation, which leads to color change. This discoloration increases especially when high concentration of purge or exudate from the meat is found which leads to pigment concentration on the meat surface.

Another major protein consumed by populations is the poultry, majorly distributed as whole frozen animals or frozen pieces. In several parts of the world, however, consumers are increasingly demanding for refrigerated poultry. One of the persistent problems of refrigerated poultry submitted to vacuum packaging is that when consumers open the package, they sometimes encounter what is referenced as “confinement odor,” derivate mainly from lipid oxidation. In general, odor is the main limiting factor for consumers to accept the product as fresh; odor issues occur in general prior to the amount of bacteria achieve critical levels [10].

In summary, analyzing contributing elements for meat quality, the first one is the meat product itself (muscle and fat) and its initial microbial counts which can result on off-odor and gas production, discoloration, and changes on flavor. For processed meat products, the formulation is a key factor on shelf life, depending on ingredients and preservation method uses—e.g., cure, smoking, cooking, etc. The second parameter is the gas environment around the meat, associated with vacuum packages and MAP to control microbiological growth and chemical reactions. Light has also impact on color of meat due to interactions with pigments. The last critical parameter is the storage and transportation temperature which directly affects the decay rate, microbial growth, and dripping. Correct packaging design associated with good manufacturing practices and proper transportation and storage are key to deliver a high-quality product to consumers.

3. Packaging processes and requirements

There are several packaging possibilities available in the market to be used with meat products, comprising different materials such as metals, plastics, and carton. This chapter is fully dedicated to explore the different combinations for plastic packaging, a very versatile and efficient packaging presentation for such products used in formats as vacuum packages, modified atmosphere packaging, pasteurization, sterilization, freezing, and other nonthermal processing such as high pressure processing (HPP).

3.1 Flexible packaging components

Meat products are broadly packaged using flexible plastic packaging materials or a combination of flexible plastic packaging and rigid containers or carton boards. As packages are in general subjected to low storage and transportation temperatures, mechanical strength of polymeric materials is a must for proper protection of packaged goods in the final applications. Since first wraps are based on polyvinylidene chloride (PVDC) polymers till multilayer films with a combination of several attributes, meat packaging is one of the most complex fields into food packaging, combining a list of materials and processes to achieve proper protection, allowing consumption into the most remote areas of the planet.

Several material families are abundantly used in packaging structures, highlighting polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), ethylene vinyl alcohol (EVOH), polyamides (PA), and PVDC as well as different copolymers within such polymer families.

Aiming to illustrate the main elements of meat packaging, the different features can be bundled into few elements that provide food protection: (1) sealing for proper hermeticity, (2) barrier to provide proper internal environment for food protection, and (3) abuse resistance to avoid failures due to mechanical impact and/or internal puncture from cured and bone meat pieces. The different elements are combined into single packaging structures via modern processes such as coextrusion, which multiple extrusion screws pump materials into a single extrusion die and combine the materials all together, adding up to 13 layers of different materials to deliver all needed packaging features. Another traditional methodology to combine flexible polymeric packaging materials is to adhere all together using lamination adhesives and/or extrusion coating. Although both processes can provide proper functionalities, the use of coextrusion has grown rapidly during the last years over lamination as it simplifies production process, eliminating one step and producing packaging films with all performance requirements directly from extrusion.

The role of packaging designers, from the material selection to the fabrication process selection, is key to maximize the packaging impact on extending product shelf life, reducing footprint from both packaging and product and providing correct end of life for recycling, reusing, or disposing.

3.1.1 Sealants

Sealants are the first key element on a proper packaging design, especially for vacuum and modified atmosphere packages. The most common sealing or welding methodology is based on heat sealing, either using constant heated sealing bars, induction sealing, or impulse sealers, always targeting for fastest possible sealing process to guarantee maximum productivity in a packaging line.

Equal to thermal processes, ultrasonic sealing also generates material melts to achieve molecular bonding of the layers. The major difference is that heat is generated internally in the packaging material itself by mechanical vibration rather than by conduction from the external layers to the inside sealing surfaces.

The selection of a sealing material for a flexible packaging structure depends on deep analysis of packaging usage requirements, filling process and machinery, possible product contaminations in the sealing area, and possible thermal processing. Hermetic sealing is obtained when the sealant material from both packaging faces can be untied and remains tied till consumption moment.

The parameters involved in a sealing process are basically the temperature of the interface to be melted, the melting temperature of the polymer, the polymer chain diffusion rate, melt strength, and crystallization rate. When melted and pressured, the

two surfaces are in contact over a wide area and in fractions of seconds the diffusion of chains between the two sides occur, creating “molecular entanglements”—the chain diffusion is mainly due to Brownian movements of molecules and chains reptation [11]. After cooling, polymeric chains are recrystallized and hold the surfaces together. The main objective of sealing process is to create a hermetic bundle that prevents packaged content to leak, a factor that is imperative for vacuum and MAP formats. For packages that are subjected to thermal processing such as pasteurization or sterilization, besides hermeticity, the seal strength is another key variable to be considered during sealant material selection.

If mechanical stress is applied to separate the two surfaces while the material is still molten, the “entanglements” generated by chain diffusion generate a force called hot tack strength. This property is especially important for automatic packaging machine. If there is a minimum time of cooling and crystallization, the property is called heat seal strength—it can be measured after a certain time in a universal testing machine.

The main materials used as sealing layers or webs in flexible packaging are PE and its copolymers. PE was accidentally discovered in the early 1930s and in few decades becomes the largest volume polymer produced globally reaching a total close to 100 million metric tons per year. Based on ethylene polymer backbones and with wide range of comonomers technically available to be combined with ethylene, this polymer family presents a broad range of mechanical and thermal properties due to the combination of crystalline and amorphous proportions. PE molecular architectures can be composed of linear or branched molecular segments defined by the different polymerization and catalyst technologies available commercially. Traditional division of different polyethylene types by density is described in **Table 1**.

Packaging designers generally select PE resins at density ranges below 0.920 g/cm³ as sealants materials, more preferably the ones produced using single-site catalysts (also known as “metallocene resins”) due to their homogeneous composition and superior sealing properties. Metallocene polymers represent the newest class of PE made using molecular catalyst systems, with just one reactive metal center surrounded by molecular structures that hinders access of different monomers and comonomers during polymerization process. These molecular catalysts can control molecular parameters in higher degree when compared to the heterogeneous systems as Ziegler-Natta or chromium catalysts. The result is a very narrow distribution of comonomers across the polymer composition and sharp melting point.

The lower the density, the lower the heat-sealing temperature, meaning packaging can be sealed faster or using reduced energy amount. The heat seal initiation temperature (HSIT) has been obtained when the surface temperature reached an amount of amorphous material of 77% for PE [12]. Lower heat seal initiation temperature means that crystal domains of PE microstructures are small and with multiple defects, being easily molten to create a flowing material for heat-sealing

Resin family	Density range (g/cm ³)
High density polyethylene (HDPE)	0.941–0.965
Medium density polyethylene (MDPE)	0.925–0.941
Linear low density polyethylene (LLDPE/LDPE)	0.915–0.925
Very low density polyethylene (VLDPE)	0.900–0.915
Elastomers/plastomers	0.865–0.905

Table 1.
Classification of different polyethylene by density.

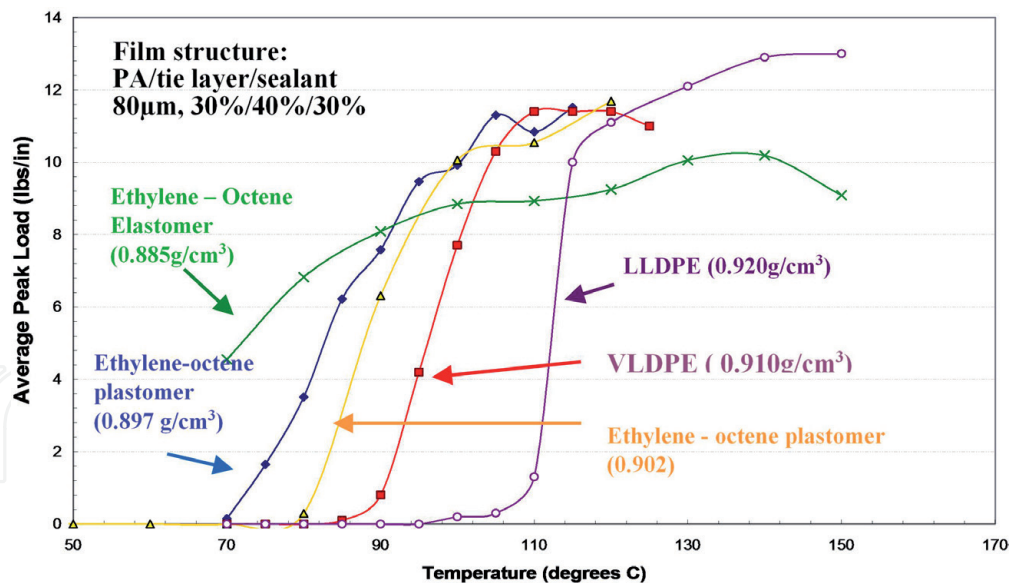


Figure 1.
Effect of polyethylene resin density into heat-sealing behavior of different sealing resins.

purposes. **Figure 1** demonstrates the effect of PE resin density into heat-sealing behavior of different sealing resins, highlighting the broad range of thermal properties a PE resin can achieve depending on the amount of comonomer incorporated to reduce density.

For meat packaging applications, it is very common to have contaminants such as grease, blood, and meat purge in the sealing area during packaging filling. In order to have proper sealing, materials with low-melting temperature are able to flow around contaminants or push them outside the sealing area to provide hermetic sealing. In the case of vacuum bags, the presence of folds and wrinkles is also very common, leading to hermeticity problems as small channels are formed in between the two sealed packaging webs. Sealant materials such as ethylene-based polyolefin plastomers (POP) and elastomers (POE) are best options to solve these problems and create hermetic packages due to their sharp melting point and low viscosity during heat-sealing processes. The ability to seal through contamination and close securely the microchannels is denominated in the industry as caulkability. Commercial brands of POP are Affinity™ from The Dow Chemical Company and Exact® from Exxon Mobil.

Sealants based on ethylene copolymers can also present different features when polar comonomers such as vinyl acetate, methacrylic acid, ions, etc. are added to the polymer composition; very particular properties can be obtained. Ethylene vinyl acetate (EVA) resins were used in blends with polyethylene materials few decades ago to reduce melting temperature of the sealant composition till more efficient plastomers were found and applied for meat packaging. Particularly in the case of shrink barrier bags, EVA copolymers can present a dual role, as they serve as sealants and also tie layers for the PVDC barrier layer. EVA polymers can be found in different suppliers such as the Dow Chemical Company with Elvax® and Braskem.

Within ethylene-based copolymers, analyzing specifically the meat packaging applications, ionomers are a class to be highlighted due to some unique features. Ionomers are based on a copolymer of ethylene with carboxylic acid and partially neutralized with ions, forming a polymeric structure with ionic bonds within its microstructure [13]. They were created and commercialized by Dupont since the 1960s under Surlyn®, with products based on Zn, Na, and K ions for different packaging and non-packaging applications. Such chemical structure creates a polymer with reduced crystallinity, enhanced clarity, superior sealing properties, especially



Figure 2.

Vacuum packages with polyethylene and ionomers as sealants and the combined effect of secondary seal and protein adhesion.

when sealing area is contaminated with liquids or fine powders, and strong interaction with different proteins present in the meat products. The intimate interaction of packaging and meat product [14, 15], particularly for Na- and Zn-based ionomers, is known as protein adhesion and used in many applications such as vacuum bags, thermoformed trays, and skin packaging to reduce the amount of purge liquids to be trapped in between the packaging material and the product, enhancing shelf appeal and extending shelf life. Another complementary feature found in ionomer sealant materials is the ability to generate strong adhesion between two film surfaces under vacuum when exposed to temperatures up to 90°C for few seconds. This adhesion is denominated by secondary seal and, associated with protein adhesion, creates a unique shelf appearance for vacuum packages as well as skin packages. **Figure 2** demonstrates two examples of vacuum packages, one with standard polyethylene sealant and another ionomer as sealants and the combined effect of secondary seal (water bath 85°C during 1 second) and protein adhesion.

In general sealed packages need tools as scissors or knives to be opened by consumers, but on the other hand, several packaging presentations are already commercialized with special sealant compositions that allow hermeticity to be maintained along all transportation and storage process but can be easily open by a consumer. There are two main mechanisms to create easy open seals: the first one is based on the delamination of sealing material from the adjacent layer, and the second one is obtained by selected polymer compositions with a certain level of incompatibility to generate cohesive failures when subjected to pulling stresses. For the delamination or burst peel, combinations of ionomers as sealants and HDPE as backing layer are a possible choice, and for cohesive failure, there are different formulated products such as Appeel® and Sealution™ from the Dow Chemical Company designed to be sealed into different materials such as PET, PP, PS, and PE and present easy open characteristics. Several other product combinations such as polybutylene (PB) and EVA, PB and LDPE, and ethylene acrylic acid (EAA) and LDPE can also be tailored to generate easy open properties.

A second product family to be highlighted as potential sealant layer for meat packaging is polypropylene and its copolymers. This class of sealants present higher melting point, from 140 to 161°C, and can stand sterilization processes that uses high-temperature exposure with no leakage. Packaging structures containing PP as sealant materials can be used in several packaging formats such as pouches, thermoformed trays, and vacuum bags.

3.1.2 Barrier resins

Once proper sealing is achieved in a given packaging, a second key element for meat packaging design is barrier layer. Different meat products require different gas and water vapor barrier protection. At the same time, different packaging materials can present the ability to modify the movement of gases and vapor molecules when different partial pressures of gases and vapors are found in either side of the packaging materials creating a flux from regions of high concentration to regions of low concentration. Permeability is defined by polymeric material ability to allow gases and vapor absorption on packaging surface and the transportation rate in the bulk of the polymer, being the first driver dependent on solubility parameters of permeant on polymer and the second on the free volume, crystallinity levels, and chain flexibility to allow permeant to move through polymer structures. **Figure 3** describes typical permeability ranges of main materials used for packaging films for two main permeants that can affect food quality, oxygen (O₂), and moisture.

For meat packaging applications, one of the pioneer materials used in such structures was the polyamides (PA), extensively applied on barrier packaging or as mechanical enhancer for heavy duty applications. Flexible packaging market recognized coextruded films with PA layers as structures with high tensile strength, improved thermoformability as well as enhanced impact and puncture resistance, being the sole election for applications such as bone-in meat.

PA resins are a large group of polymer structures, developed originally by DuPont in 1939. Polyamides are mostly aliphatic, linear polymers composed by the amide group, as repeating unit in the polymer chain, separated by hydrocarbon unit. Polyamides may be synthesized either by (A) polycondensation of divalent carboxylic acid and divalent amines or by (B) polycondensation of difunctional amino acids containing both one amine and one carboxylic acid functionality in the same molecule [16]. The amide groups are capable of forming strong electrostatic forces between the –NH and the –CO– units (hydrogen bonds), reducing free volume and therefore permeability, producing high melting temperatures, strength and stiffness, and chemical resistance. The increasing number of amides groups into the molecule increases the number of hydrogen bonds and reduces free volume, reducing gas permeability as well.

The most used PA resins for multilayer packaging structures are polyamides 6, 6.6, 11, and 12, the copolymers such as PA 6/6.6 and PA 6/12, and the terpolymers

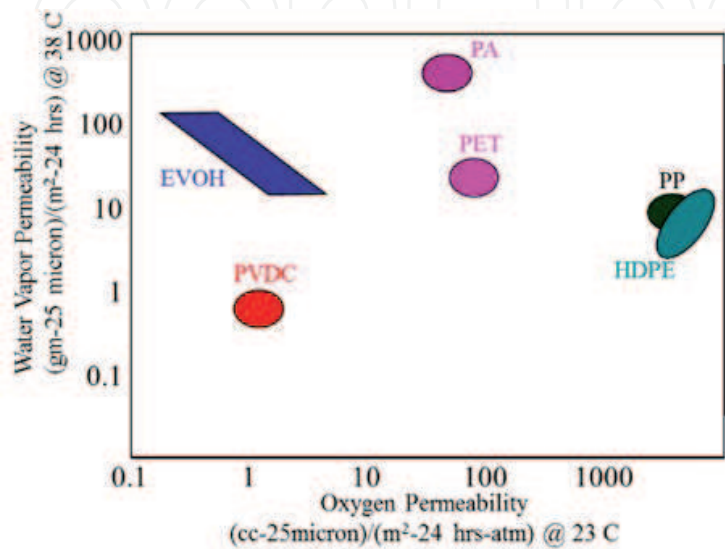


Figure 3.
Typical permeability ranges of barrier materials for food packaging.

as PA 6/6.6/12. The PA is used in general as core layer, surrounded by polyolefin tie layers and PE resins as external and sealing layer. The resulted packaging films combine hermetic sealing, improved toughness and medium O₂ barrier.

The amide units present strong interactions with water, motivating PA resins to absorb water from 2 to 20%. These water molecules are inserted into the hydrogen bonds, loosening the intermolecular attracting forces and increasing gas permeability through the polymer. The different PA compositions exhibit a melting temperature ranging from 178 to 260°C and different levels on moisture absorption—the higher the melting point, the higher the potential water absorption. The reduction on crystallinity is also found in copolymers and terpolymers, resulting on higher transparency, higher free shrinkage, improved thermoforming, and higher puncture resistance. As terpolymers are more permeable to gases, this material class can be advantageously used for certain meat products as vacuum-packaged salamis that demands a certain CO₂ permeability. Commercial producers of PA include UBE and BASF.

Another class of barrier polymer is ethylene vinyl alcohol (EVOH). First commercialized by Kuraray in 1972, it is a polar polymer widely used as oxygen barrier material for several applications in packaging industry, including meat packaging. As a semicrystalline copolymer of ethylene and vinyl alcohol, it also presents strong interactions among each polymer chains (inter- and intramolecular bonding) that leads to improved gas barrier performance, similarly to the mechanisms described for PA.

Along the years, EVOH has gained participation into packaging markets by replacing metallized films and foil due to its superior barrier maintenance when subjected to flex cracking. This barrier material presents good processability, and it is generally used as core layer into coextruded films in combination with polyolefin type of sealants and a tie layer based on a polyolefin modified with maleic anhydride. This is particularly relevant for EVOH due to its hydrophilic nature, with water molecules interacting with polar hydroxyl groups in EVOH when exposed to humid environments, leading to a plasticization effect that distance between adjacent molecules (free volume) particularly into the polymer amorphous phase [17]. The impact of moisture into EVOH barrier properties is well-known [17–19], and its performance as barrier material will be dependent on environmental conditions; the final package will be exposed.

Coextruded films are rapidly demonstrating high potential to reduce the impact of moisture into EVOH polymers, serving as an important tool for improved packaging design. Two approaches are generally used to protect EVOH from humid environments, the thicknesses of the layers protecting EVOH and the moisture barrier layers of such grades, being the most effective solution is the use of a material with higher moisture barrier in the side with highest relative humidity and a material with lower moisture barrier in the side with lower relative humidity [17, 19], concluding that it is not sufficient to pack EVOH layers in between thick high-moisture barrier layers, but the asymmetric design can deliver improved performance even with thinner layers. Combinations of EVOH with other polymers are also commonly found in the different packaging structures. Coextruded films based on EVOH, PA, and polyolefin polymers can present unique features as high barrier, improved mechanical resistance, and sealability to form hermetic barrier packages in thermoformed, vacuum bags, pouches, and other formats.

The level of oxygen barrier on EVOH resins is determined by the ratio of vinyl alcohol and ethylene fractions randomly distributed into polymer chains, determining factors for crystalline levels of EVOH resins. Higher levels of ethylene create more flexible polymer chains, resins with reduced melting point, crystallinity, and increased free volume, allowing more gas molecules to permeate through the system. EVOH resins with reduced ethylene contents present improved oxygen barrier properties, reaching levels lower than 1 mL.m⁻².day⁻¹ at commercially used

thicknesses, but are more rigid and with higher melting point, resulting on packaging films with poorer mechanical performance. Considering recent advancements on extrusion controls for layer thicknesses and its variability, it is becoming more common to find commercial products with EVOH layers from 2 μm (vacuum bags) to 20 μm (thermoformed films), making this barrier resin a very competitive solution for high barrier applications.

A very particular barrier material is the chloride-based polymer-denominated PVDC. It is essentially a polyvinyl chloride (PVC) with a second chlorine atom per monomeric unit, representing a molecule with around 70% on weight of chlorine composition, creating a material with extremely reduced free volume that resulted in low permeability to gases. It was created during the 1960s by the Dow Chemical Company targeting to generate packaging films that extend shelf life of different food products through controlling oxygen and moisture permeability [20, 21], something unique as most of the polymer provides barrier for just one or another. PVDC homopolymers, however, due to their strong intermolecular forces, present melting temperatures from 198 to 205°C and degradation temperatures close to 210°C [22], reducing operational window available for proper extrusion of flexible packaging structures. In order to expand the extrusion processing boundaries, different comonomers such as vinyl chloride and methyl acrylate are added to the molecular structure and reduce melting point and expand processing window in 40–50°C [22], being the first type of comonomer mostly used in monolayer film applications for household wraps and sausage chubs and the second in coextruded films for fresh meat packages. All commercial PVDC resins are copolymers.

Coextruded films that use PVDC as barrier layer are in general composed of polyolefin external layers and EVA as tie layers. EVA polymers, generally with 9–18% VA contents, present enough polarity to provide proper adhesion to PVDC and polyolefin layers in a five-layer structure or decent sealing performance when just three layers are available. Combine PVDC polymers with other materials that demand higher processing temperatures such as PA and PET are quite challenging with traditional extrusion processes due to the low degradation temperature PVDC has, becoming usual to have PVDC barrier resins combined with low-melting temperature polyolefin grades as plastomers and ethylene copolymers such EVA.

When different barrier resin alternatives are considered for a meat packaging structures, one particular topic to assure proper protection along all product shelf life is the barrier maintenance when exposed to high-moisture environments. PVDC permeability properties are unaffected by relative humidity, delivering the

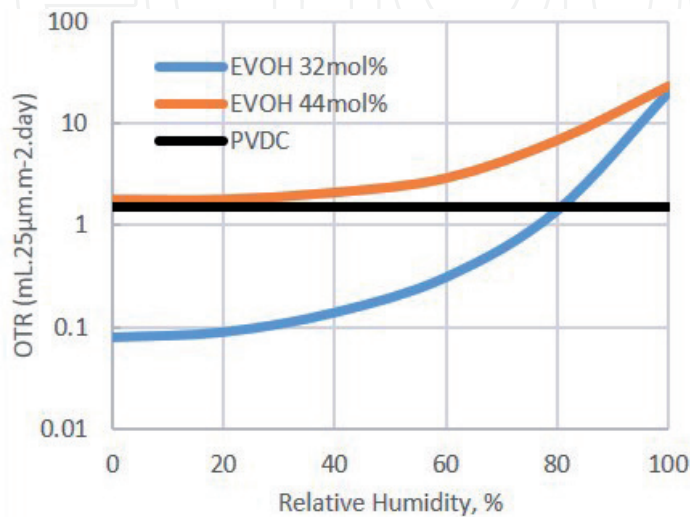


Figure 4.
Oxygen permeability for different barrier materials when exposed to several moisture levels.

same protection for dry and high-moisture environments. This particular feature was one of the main reasons PVDC is the dominant barrier technology for fresh meat packaging shrinkable films around the world, allowing the meat to reach shelf life levels up to 100 days.

Figure 4 demonstrates the impact of moisture on oxygen barrier properties of several typical barrier package films.

3.1.3 Abuse layers

Mechanical requirements in meat packaging applications are strong dependent on product characteristics, packaging processes and storage, and distribution environments. The type of meat product is the first element to be evaluated during the definition of packaging structures and thicknesses. Meat pieces with bone tips, cured skins, and sharp edges are the most critical class and demand packaging films with high puncture resistance. This property, however, can be divided into two different variables, puncture force and puncture deformation at break, and each of them is important for different aspects of packaging chain.

The combination of meat pieces with sharp edges and vacuum process can lead to complex issues due to vacuum loses after packaging. The origin of such issue is the vacuum process itself that projects the film on the meat surface and deforms the film on top of any existing irregularity with a very high deformation speed. When films are deformed at high speed, the time available for chains to rearrange and orient toward the applied tension is reduced, causing an early break. Lower deformation rates, in general, generate higher force responses from materials due to stress-hardening effects. Also, if packaging elongation is too high during vacuum process, the final film thickness at the tip of sharp meat piece is reduced and favors the packaging material to fail at this point with any subsequent deformation during transportation or handling. The dependence of deformation speeds on force is shown in **Figure 5** for two different coextruded films with 90 μm , the first composed of 40% PA 6 and 60% LLDPE and a second with 10% EVOH 38 and 90% LLDPE; the films with PA demand higher force to deform, while films with EVOH can deform more under lower force.

Another critical element to consider during material selection for a packaging with improved mechanical protection is the storage environment. As temperatures are reduced closer to polymer glass transition temperature, the failure mechanism of plastic packaging moves from ductile to fragile, reducing the capacity of plastic materials to absorb energy due to deformation under stress. These properties, however, can be manipulated by molecular design and polymer compositions that increases polymer flexibility and creates semicrystalline structures with improved toughness. An example of two different polyethylene resins with the same density and different dart energy responses at a range of temperatures are described in **Figure 6**.

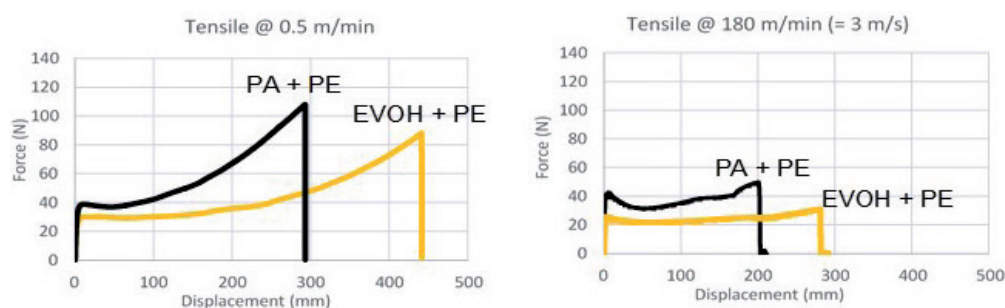


Figure 5. Tensile force response of two packaging films (PA + PE and EVOH + PE) deformed at two different rates.

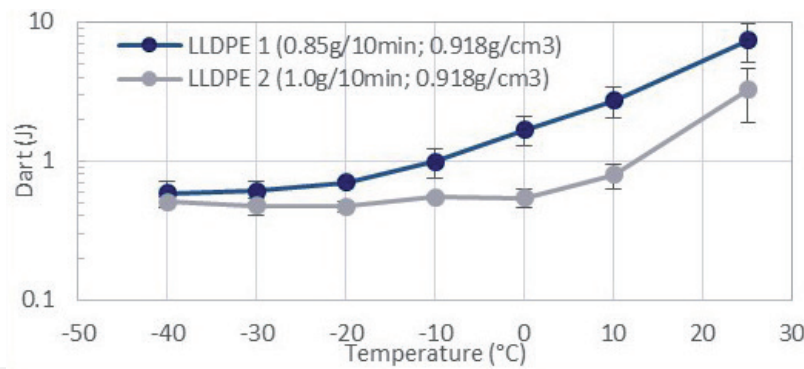


Figure 6.
 Effect of environment temperatures on impact energy of PE resins.

The LLDPE 1 presents improved dart resistance vs LLDPE 2 for temperature ranges from -40 to 25°C , although the difference is smaller when temperatures are reduced to ranges toward PE glass transition temperature.

3.2 Packaging applications and formats

There are several studies [4, 7] that also indicate packaging as the main alternative for most of the brands to communicate with consumers at sales point; in Brazil, for example, 81% of purchase decisions are made in front of the shelves. About 10% of brands exposed in supermarkets have support from advertisement tools in television, magazines, and the Internet to promote their products; all the others rely on their own packaging to convince consumers to be the selected one during purchase process.

Packaging presentations and formats are chosen depending on packaging technologies that meat processors have access to purchase, can afford, and have proper machinery to use it besides all understanding on target consumers and market position. The same meat product can be packaged with simpler packages as film wraps to highly engineer packaging films with improved food protection and added consumer convenience through easy open, reclose, and improved shelf appeal.

One of the simplest packaging formats currently in use are non-barrier bags or plastic wraps, combined or not of trays or paper wraps, generally found at butcher stores or small supermarkets. Butcher shops still represent a traditional form of meat product purchase, and packaging used can protect meat against environmental contaminations, but no barrier to oxygen or moisture losses are expected from this type of packaging.

Another simple packaging presentation commonly used by retailers is the combination of trays made from polystyrene (PS), expanded polystyrene (EPS), PET, with PVC based wraps, or shrink films. For fresh beef, this combination has enough oxygen permeability ($\sim 60,000 \text{ mL} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$ 23°C and 90% RH) to form oxymyoglobin on meat surface and maintain its red blooming color, an important factor on customer perception of fresh meat quality. PVC wrap can be manual or automatically applied, being heated at the bottom of the package to maintain the dimensions but with no hermetic sealing is achieved, allowing purge liquids to leak from package. As no barrier films are employed, packaging itself has minor influence on meat product shelf life. This type of packaging has an average thickness of $7 \mu\text{m}$, the tray and film wrap weights from 15 to 20 g for a 1 kg portion, and fresh meat pieces packaged with this technology have an expected shelf life of 3–7 days when $1\text{--}4^{\circ}\text{C}$ are used for storages. For poultry packages, there are some other shrink films based on PE that in combination with EPS trays are used as packaging of freshen and frozen poultry, but no barrier or hermeticity is obtained.

Vacuum barrier packaging types, on the other hand, restrict oxygen access to meat surface (OTR levels from ~ 5 to $20 \text{ mL} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$ at 23°C and $90\% \text{ RH}$), reducing the growth of spoilage bacteria such as *Pseudomonas* and favors the competing *Lactobacillus* species. Film structures can be based on EVOH and PA combinations with PE as sealants and possibly external materials with high thermal resistance such as PET—extrusion tie layers are needed to combine all distinctive layers. For refrigerated fresh meat, optimum storage condition is in the range of $1.5 \pm 0.5^\circ\text{C}$ [5] and residual oxygen levels as low as $0.15\text{--}0.20\%$ [8]. On color, on the other hand, with the absence of oxygen, the formation of reduced myoglobin is favored, which results on a fresh meat with purple color tone. For processed meat products, the low OTR levels obtained with this packaging film help with color preservation and minimize fat oxidation, contributing to extend shelf life.

There are several types of vacuum package presentations used for meat products available in the industry, being the most common nonshrink vacuum bags, thermoformed packages, shrink barrier bags, and vacuum skin packaging.

Nonshrink barrier bags were one of the first presentations of meat packages available in the market, remaining today as a competitive alternative especially for processed meat goods such as cured pieces and sausages for wholesale. These packages are in general made from a preformed bag that receives the meat product, vacuum is applied till preset values, and subsequent heat sealing is performed generally using impulse sealing bars. These packaging films are based on coextruded structures with PA and/or EVOH as barrier layers, maleic anhydride-modified polyolefin as tie layers, and PE or ionomers sealant layers, adding from 5 to 9 distinctive layers with total thicknesses ranging from 70 to $150 \mu\text{m}$ depending on packaging size. From the packaging material requirements, polyethylene can provide hermetic heat sealing, even with grease or purge contamination, and ionomers deliver a combination of hermetic sealing and secondary sealing, eliminating meat exudate areas. Barrier layer types and thicknesses are selected according to gas permeability needs for each of the products. The packaging of selected bone-in meat products demands packaging films with enhanced puncture resistance and high-oxygen barrier, which are obtained by the combined use of EVOH and thick PA layers or EVOH and ethylene copolymers with improved puncture resistance such as ionomers, ULDPE, and metallocene LLDPE.

In order to improve shelf appeal and reduce packaging weight, a new packaging format with shrink properties to better shape packaged good was introduced into the market. The shrink barrier bag technology was originally developed by W.R. Grace (now Cryovac division of Sealed Air), and it is currently being practiced by other companies around the world. It consists on a biaxially oriented packaging structure produced via double or triple-bubble processes that is bottom sealed into a bag and receives the meat piece; after it, the vacuum is pulled, and the package is hermetically sealed using impulse sealing bars. The formed bags are submitted to contact with hot water or air (from 60 to 90°C) for few seconds and shrink forming a protective layer very close to the meat surface. Shrink barrier bags are the most efficient packaging solution when the ratio of the packaged product and packaging weight is considered; a 3 g shrink barrier bag can take the shelf life of a fresh meat piece up to 90 days when refrigerated at 0°C .

The film structures use majorly PVDC as barrier layers. A typical film structure takes also sealant layers of POP- and EVA-based tie layers adding 90% of film composition; PVDC barrier layer adds the remaining 10% of film weight. After extrusion, the films are in general subjected to crosslinking processes allowing proper dimensional stability during transportation and the possibility to overlap bags during sealing process without having one sticking to each other. Total thickness varies from 50 to $70 \mu\text{m}$. The film can be printed, or labels can be inserted internally into the package.

Thermoformed trays are another type of packaging used to pack meat products. The packages are generally formed by the use of two film structures, one for the bottom part of the package, with 100–300 μm , and another for the lid, with 60–150 μm , adding a package weight close to 10 g for 1 kg package size. The thermoforming process to form the bottom of the package is based on three steps: (1) the bottom film is heated by a heated metal plate, (2) the film is vacuum formed into a tray, and (3) the bottom tray and lid film are sealed together after the package is filled with product. Alternatively to vacuum, a mixture of gases can be injected into the thermoformed packaging to create proper atmosphere for meat preservation. In this case the bottom film used to be a rigid or semirigid structure.

The film used for thermoformed bottom tray should have good thermoformability. This performance is related to the final thickness distribution along all tray profile after vacuum forming; thicker tray walls offer improved mechanical strength and reduced gas permeability to preserve food. Tray corners are the most critical spots, presenting, in general, final thickness after thermoforming reduced to 25% or more of the original film thickness. Combinations of PA and EVOH in coextruded films with polyethylene are in general the selected packaging structure for thermoformed bottom trays, as it combines excellent thermoformability and toughness of PA, with low oxygen permeability from EVOH and hermetic sealing from polyethylene. There are also EVOH grades with improved thermoformability, allowing deeper trays (more than 7 cm deep) to be formed with proper barrier maintenance along the tray profile.

MAP is used as an alternative to preserve fresh meat while maintaining its red blooming color, creating a positive combination of shelf life extension and improved shelf appeal. Structures used for MAP can be composed of flexible thermoformed trays and lids or rigid barrier thermoformed trays and flexible lids. Ideal designs for MAP are in general heavier (30–40 g) than simpler vacuum packaging structures due to the needed proportion of product and gas volume from 1:1 to 1:3, demanding higher head space. The complex barrier structure combined to higher weight increases total packaging cost when compared to vacuum bags, fact that drives MAP to be found in single or small premium portions that are ready to serve.

VSP are the latest vacuum packaging technology introduced for meat products. It consists on a rigid tray and a flexible plastic skin formed around the packaged good, creating a new possibility for the consumers to interact with a packaged meat piece. Due to premium appearance and general high cost, it is used to pack premium beef cuts and single pieces, being able to extend shelf life of fresh meat products from 21 to 35 days with a packaging weight of 13–19 g. VSP are growing very fast and expanding its reach to several other meat products, with strong penetration into cured meat pieces, with single pieces, premium presentations as well as poultry, following similar positioning.

During packaging process, the meat is placed on the rigid tray (premade or thermoformed in line), enters into a chamber where flexible film is being heated, and will be vacuum formed around the packaged good. The process itself is similar to thermoforming, but for VSP the formed films are heated at much higher temperatures, achieving values from 150 to 220°C to allow proper forming around most complex food shapes and formats. The packaging film needs to combine the required barrier to protect the meat piece, very high transparency to allow proper visualization of the product, puncture resistance for bone-in meat pieces, hermetic sealing to avoid contaminations, and easy open to facilitate consumer access to the product. Typically, the forming film structure is based on ionomer or easy open compositions as sealant materials, oxygen barrier layers, and overall high puncture resistance materials as ionomers, ethylene plastomers, or EVA. Films can also be subjected to crosslinking processes to improve their thermal resistance and formability around complex food products.

Format	Expected shelf life	Typical packaging weight
EPS tray and PVC wrap	5–7 days	17 g
Shrink barrier bags	90 days	3–5 g
Thermoformed trays	30–35 days	6–10 g
MAP	14–21 days	30–40 g
VSP	30–35 days	13–19 g

Table 2.
Different meat packaging formats existing into the market, expected shelf life, and typical weight of each format.

As a summary of commercially available fresh meat packaging technology, **Table 2** presents a scheme of packaging alternatives, expected shelf life, and typical weight of each format.

Retort packaging is a particular packaging structure that is designed to fulfill the requirements of retort preservation process and used to pack cooked meat and ready meals. The retort process subjects packaged products to temperatures from 115 to 150°C inside pressurized autoclaves to sterilize the food for periods ranging from minutes to few hours, resulting on a final product that is shelf stable at room temperatures for several years. Film structures for retort packages are in general laminated multilayer films with higher melting point sealant materials as polypropylene homopolymer, barrier layers composed by aluminum foil, SiO_x- or AlO_x-coated films or coextruded EVOH-based films, and laminated external printed layer based on PET. The packaging films used for retort packages should be thermal and chemically stable to stand the retort temperatures without the migration of chemical compounds into the packaged product above limits established by legislations.

Some typical structures for the different packaging formats are described in **Table A1** at Appendix. Selection of materials within each product family is critical to adequate the film performance to each of packaging machinery and operational conditions existing into the market as well as different products to be packed.

4. Innovative solutions for meat products

The packaging used for food products has several functions among its life; it has evolved to attend the demands and needs of the current social organization we have today. Packaging has evolved since the beginning of its creation, being today a highly complex piece of engineering that is targeted to preserve food with minimum amount of material to be economically viable and designed for minimum environmental impact [7]. The society, however, continues to demand new solutions that enhances life quality and solve new challenges, including accessible quality food.

Food protection and preservation are two basic features of every packaging technology introduced into the market, but in the recent years, a growing concern on packaging waste has been raised in the different regions of the world. Packaging design has a major impact on recyclability, leading manufactures to progressively frame their packaging with recyclability as a clear driver. The election of certain materials in detriment of others has a direct impact the expansion of different recycling chains.

Although PVDC containing packages are still dominant technology for fresh meat packaging around the world, with more than 500K MT of packages being produced annually, concerns with chlorine-based polymers end use and by-products

formed during incineration are raising globally [18] and led the industry to find possible alternatives to produce shrink barrier bags with EVOH as alternative barrier technology. Europe was the pioneer continent to adopt such technology, led by developments on triple-bubble extrusion processes that combined EVOH as barrier technology with different materials for sealing, mechanical and moisture protection, and thermal resistance. Such process eliminated the need of irradiation step into oriented films as high thermal resistance materials can be used as external layers and allowed bags to be overlapped during sealing process without sticking to each other. EVOH-based shrink barrier bags accounts today for roughly 15% of shrink barrier bag market.

Shelf life maintenance in high-moisture environments was always a critical concern from meat producers to adopt EVOH-based shrink barrier bags. Recent study [15], comparing highly engineered multilayered shrink barrier bags based on EVOH barrier layers and different polyolefin resins and traditional PVDC based bags, was performed and has indicated both packaging solutions achieved similar meat quality levels, under controlled storage. Such indications and raising concerns with chloride-based polymers reinforce the potential growth of shrink barrier bag presentations based on EVOH barrier layers.

Poultry packaging industry, on the other hand, has created several alternatives to extend shelf life of refrigerated chicken using structures that possess agents to capture odor of vacuum-packaged chicken or use MAP to extend the product shelf life. The packages with odor absorption technologies can allow vacuum-packaged chicken to stand longer storage periods and be consumed with reduced odor perceived when consumers open the packages.

It is not just packaging materials and novel manufacturing processes are fulfilling the main demands from meat packaging industry, there are several technologies on design and functionalities that also contribute to enhance food protection and consumers experience [23]. After the consolidation of easy-to-open packaging presentations, the possibility to close it again is also spreading for several packaging types. The reclosability can be obtained through the use of zippers or other closure devices and more recently through the use of specially designed lids with pressure-sensitive adhesive compositions, such as M-Resins[®] from Bostik, in one of the internal film layers. The lid film is sealed on a tray, and when the lid is pulled, the film has adhesive or cohesive failure and exposes the sticky internal layer, creating a reclosable possibility that helps with food preservation during consumption period.

The new organization and size of families today also have created a new demand for food industry, reducing packaging sizes or creating packaging presentations with multiple small portions to be consumed along a period. The long commute journeys in big cities also increased the demand for food products that could be consumed on-the-go, based on smaller packages, generally barrier trays or retort pouches that contain cured meat, soups, stews, and baby food products. Convenience is another big demand from consumers today, targeting to food presentations that are convenient to consume and easy to prepare, without deprive demands of healthy and fresh food. In face of such demand, the industry has created options of entire recipes packaged using MAP for a quick finishing at home, ovenable packaging structures and cooked ingredients to help meal cooking process, without eliminating the individual cooker touch and fresh food impression [23].

Advancements on food sterilization technologies are creating novel meat products presentations and demanding new packaging solutions. Retort packaging is a traditional sterilization technology used for meat products, but new approaches are gradually being adopted due to different benefits such as longer shelf life, elimination/reduction of food preservatives, as well as nutritional and flavor preservation [24, 25]. High pressure processing (HPP) uses high pressure from the compression

of a fluid medium such as water, ranging from 300 to 800 MPa, in general combined with certain temperature exposure (form to sterilize meat products. The process inactivates harmful and food spoilage microorganisms, being more effective on microorganisms with greater structural complexity—e.g., parasites are more susceptible than virus [25]. This process was adopted for some meat products such as cold slices and meat-based ready meals. As packaging exposed to this process are subjected to high pressure, they need to be able to accept up to 15% reduction in volume and recover its volume after pressure is released, maintaining hermeticity, strength, and barrier properties. Common packaging structures for this process are based on barrier trays and lid combinations and barrier vacuum-sealed pouches.

Other sterilization methodologies are being explored in certain applications, and there are few examples also for meat products. The use of microwave for pasteurization process ready meals has been explored to extend shelf life and create shelf stable food presentations, always combined with oxygen and moisture barrier packaging structures. Even newer approaches as the use of plasma and electric fields [24] are being explored to inactivate pathogenic microorganisms and improve food safety but still in early exploration phases.

Another major demand from modern consumer is the end use of packaging after it completes its main function of food protection. Although sharing partially the same comonomers, EVOH and polyethylene are not fully compatible for mechanical recycling purposes. The combination of such materials on multilayer packaging structures is, however, very common to achieve good balance of sealing, barrier, and toughness to several applications. Compatibilization technologies are available to be used during recycling process of these combined streams [26], but a new generation of compatibilizers from Dow under Retain™ product family claim to allow EVOH- and PA-based packaging films to be mechanically recycled with no extra compatibilizers added [27]. The correct amount of compatibilizer is added into discrete layers, and the material possesses enhanced dispersion capacity to create a homogeneous recycled material as well as allow the incorporations of such waste into existing PE recycling streams.

Meat product industry is continuously looking into novel ways to enhance their product offering toward healthier and safer products based on combinations of process and packaging designs. Packaging designers should be able to combine these demands into packaging structures that offer maximum food protection with appropriated end use after the completion of their function.

5. Conclusions

The first functionality of packaging is to physically protect food against external contamination and losses, from product production through the consumption in every consumer home, passing along all transportation chain and sales point exposure. If properly designed having in mind the specificity of meat product to be packaged and the main factors that drive its deterioration, packaging can also contribute to extend shelf life and enhance consumer experiences. Packaging design has a major impact on final end use, determining the attractiveness for recyclability, reuse, or final disposal of a packaging film.

Several elements should be added when designing a package, such as sealant properties and final needs on hermeticity, strength and access to product, gas barrier to control microbiological growth, and final mechanical resistance that will allow packaging to stand possible challenges during transportation and handling. Besides material selections, the production process is key to reach some desired features such as shrinkage and mechanical strength.

The plastic packaging structures used today are the result of a continuous optimization exercise performed by packaging and food chains in the last decades and continue to drive the whole industry toward the elimination of plastic waste and reduction of carbon footprint. The developments on meat processing and sanitary techniques also had a major contribution on providing safe and quality meat products to the population around the world.

Appendix

Packaging format	OTR level	Typical structure (from sealing to external layers)	Typical application requirements	Typical use
Vacuum bag	Medium	PE (POP)/tie/PA/tie/PE	<ul style="list-style-type: none">• OTR from 20 to 50 mL.m⁻².day⁻¹• High puncture resistance• Caulkability	Cured meat, sausages
Vacuum bag	High	PE (POP)/tie/PA/EVOH/PA/tie/PE	<ul style="list-style-type: none">• OTR from 1 to 5 mL.m⁻².day⁻¹• High puncture resistance• Caulkability	Pasteurized sausages, seasoned meat products
Shrink barrier bags	High	POP/EVA/PVDC/EVA/POP	<ul style="list-style-type: none">• OTR from 8 to 20 mL.m⁻².day⁻¹• >30% free shrinkage• Sealing through contamination	Fresh meat
Shrink barrier bags	High	POP/EVA/PVDC/EVA/IO	<ul style="list-style-type: none">• OTR from 8 to 20 mL.m⁻².day⁻¹• >30% free shrinkage• Protein adhesion	Fresh meat
Shrink wrap + EPS tray	Low	LLDPE + LDPE	<ul style="list-style-type: none">• Shrinkage• Printing quality	Frozen chicken
Thermoformed bottoms	Mid	PE/tie/PA/tie/PA or PP	<ul style="list-style-type: none">• OTR from 20 to 50 mL.m⁻².day⁻¹• High puncture resistance	Frozen sausages Frozen meat
Thermoformed lids	Mid	PE/tie/PA/tie/PE//PET	<ul style="list-style-type: none">• OTR from 20 to 50 mL.m⁻².day⁻¹	
Thermoformed bottoms	High	PE/tie/PA/EVOH/PA/tie/PA or PP	<ul style="list-style-type: none">• OTR from 1 to 10 mL.m⁻².day⁻¹	Pasteurized sausages, fresh meat, seasoned meat, cold slices
Thermoformed lids	High	PE/tie/EVOH/tie/PE//PET	<ul style="list-style-type: none">• OTR from 1 to 10 mL.m⁻².day⁻¹	
Rigid barrier trays	High	PE/tie/EVOH/tie/PET	<ul style="list-style-type: none">• OTR from 1 to 10 mL.m⁻².day⁻¹	
VSP	High	PE/EVA/IO/tie/EVOH/tie/IO/EVA/Easy Open	<ul style="list-style-type: none">• OTR from 5 to 15 mL.m⁻².day⁻¹• High clarity, puncture, and formability• Easy open	Fresh meat, cured meat

Packaging format	OTR level	Typical structure (from sealing to external layers)	Typical application requirements	Typical use
Retort pouch	High	PP//Al//PET	<ul style="list-style-type: none">• High-oxygen barrier• High-temperature resistance	Ready meals, cooked meat
Retort pouch	High	PP/tie/PA/EVOH/tie/PP//PET	<ul style="list-style-type: none">• High-oxygen barrier• High-temperature resistance	
/—Coextruded layers, adhered using tie layers or inherent compatibility between adjacent polymers //—Laminated films, adhered using lamination process and adhesives				

Table A1.
Typical structures for the different packaging formats.

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